INNOVATIVE SYSTEM FOR PRECISION MEASUREMENT OF HIGH VOLTAGE CAPACITANCE & TAN δ

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Abstract

This paper describes the measurement of Capacitance and Tan δ, how these are useful to the nation and its benefits to the power companies (Generating Stations, Transmission & Distribution Sub-stations and Industries). The objective of the measurement of Capacitance and Tan δ is to check the Insulation level of Electrical apparatus. The Insulation must be regularly checked so that timely maintenance can be done and failures may be averted, thereby saving the revenue. Hence by measuring these electrical properties of capacitance and Tan-Delta regularly, it is possible to ensure the Insulation unexpected breakdowns. Dissipation factor (Tan δ) is one of the most powerful diagnostic tools to monitor the condition of solid insulation of various high voltage equipments.

Key words*: Capacitance, Tan δ, Insulation*

Introduction:

Insulation failure of high voltage equipments results in the breakdown of the system and aging & electrical stress affects the electrical properties of the insulating system and after aging it is not safe to use the equipment which can be hazardous to human health.

The insulating materials are more prone to stresses like thermal and electrical stress etc as compared to the magnetic & conducting materials which form the base of all electrical equipment, The measurement of Capacitance and Tan δ will create awareness amongst the industries and users towards the deterioration and aging effects of insulation of cables, bushing & transformers etc.

Tan-Delta measurement (also called Loss Angle or Dissipation Factor) is a diagnostic method of testing electrical equipment for integrity of the insulation.

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Need of Measurement

By measurement of Capacitance and Tan δ regularly it is possible to ensure the operational reliability of High Voltage (HV) insulating systems and also to avoid insulation breakdowns involving very high cost to the user. This is particularly important for High-Voltage bushings, Power Transformers, Generators, Power Capacitors, High Tension (H.T.) cables. Measurement of Changes in normal Capacitance of electrical apparatus insulation indicates the presence of moisture layer, short circuits & open circuits in capacitance network. Increase of Dissipation factor (*Tan δ) indicates* the following condition of the insulation of electrical equipments and instruments:

- Chemical deterioration due to time & temperature
- Contamination by water, carbon deposits, dirt & other chemicals
- Leakage through cracks & over surfaces
- Ionization

Dissipation Factor (Tan δ)

Every insulation material contains single free electrons that show little loss under DC circuit with P= U^2/R. In AC circuits dielectric hysteresis loss occurs which is analogous to hysteresis loss in iron cores. As losses occur in every insulation material, an equivalent diagram of a real capacitance is constructed in Fig. 1

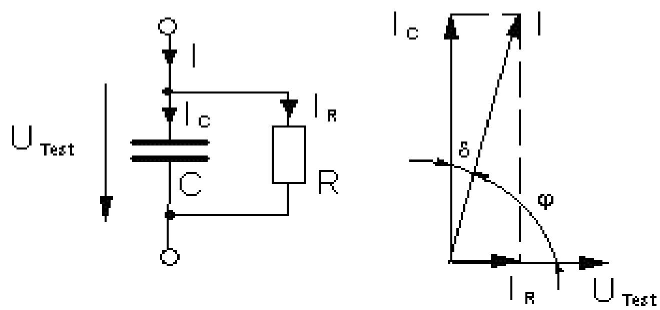

Fig. 1

Dissipation Factor:

$$\text{Tan } \delta = \frac{P_R}{Q_C} = \frac{I_R}{I_C} = \frac{X_C}{R} = \frac{1}{\omega . C . R}$$

U_{Test} Applied test voltage
I_C Current through capacitance
I_R Current through resistance (insulating material)
C Ideal capacitance

R Ideal resistance
P_R Real Power or active power due to resistance R
Q Reactive power
Q_C Reactive power due to capacitance C
PF Power Factor

$$PF = \text{Cos}\,\Phi = \frac{I_R}{I} = \frac{P_R}{S_C} = \frac{\text{Tan}\,\delta}{\sqrt{1 + \text{Tan}^2\,\delta}}$$

Because P = Q • tan δ, the losses which are proportional to tan δ, will usually be given as a value of tan δ to express the quality of an insulation material. Therefore the angle δ is described as loss angle and tan δ as loss factor.

If the insulation of a cable is free from defects, like water trees, electrical trees, moisture and air pockets, etc., the cable approaches the properties of a perfect capacitor. It is very similar to a parallel plate capacitor with the conductor and the neutral being the two plates separated by the insulation material.

In a perfect capacitor, the voltage and current are phase shifted 90 degrees and the current through the insulation is capacitive. If there are impurities in the insulation, the resistance of the insulation decreases, resulting in an increase in resistive current through the insulation. It is no longer a perfect capacitor. The current and voltage will no longer be shifted 90 degrees. It will be something less than 90 degrees. The extent to which the phase shift is less than 90 degrees is indicative of the level of insulation contamination, hence deterioration of cable quality/ reliability. This "Loss Angle" is measured and analyzed. In a perfect cable, the angle would be nearly zero. An increasing angle indicates an increase in the resistive current through the insulation, meaning contamination. The greater the angle, the worse the cable.

What Are Water Trees?

Water trees are small tree shaped channels found within the insulation of a cable, caused by the presence of moisture.

They are very prevalent in service aged Cross Linked Poly Ethylene (XLPE) and other solid dielectric cable, like Poly Ethylene (PE) and Ethylene Propylene Rubber (EPR) cables. These tree shaped moisture channels, in the presence of an electrical field, eventually lead to the inception of partial discharge (pd), which is responsible for the formation of electrical trees, which grow to a point where insulation failure occurs. The tan delta test shows the extent of water tree damage in a cable.

Status of Capacitance and Tanδ in India

National Physical Laboratory, India (NPLI) has established the standards for measurement of Capacitance and Tan δ (loss factor) in the insulation of test objects for example Transformers, Bushings, Cables etc. up to 200kV. This facility also helps calibrating kV Meters upto 150 kV with higher accuracy.

Measurement of Capacitance & Tanδ

The measurement of Capacitance & Tanδ is done through a standard capacitor and standard C & Tanδ Bridge which performs the measurements through automatic balancing [2]. The measuring system is based on the double vector-meter method which relies upon the measurement of the current I_N through the known reference capacitor C_N and the measurement of the current I_X through the unknown test object C_X. (Fig. 2) Both the branches are energized by an external High Voltage (HV) AC power source (U_{TEST}) and both currents are measured by the adjustable high accurate shunts R_X and R_N and then digitized. By using IEEE 1394 "fire wire" data bus technology each digitized value is time stamped. With this technology not only the values but also the time information (phase displacement) between I_N and I_X cab be measured very fast and highly accurate. The digitized data streams are fed into the built-in PC and over the known standard capacitor all other desired measuring values can now be determined online.
The high voltage divider measures the voltage and current input to the cable, sends this information to the controller, which analyzes the voltage and current waveforms and calculates the tan delta number.

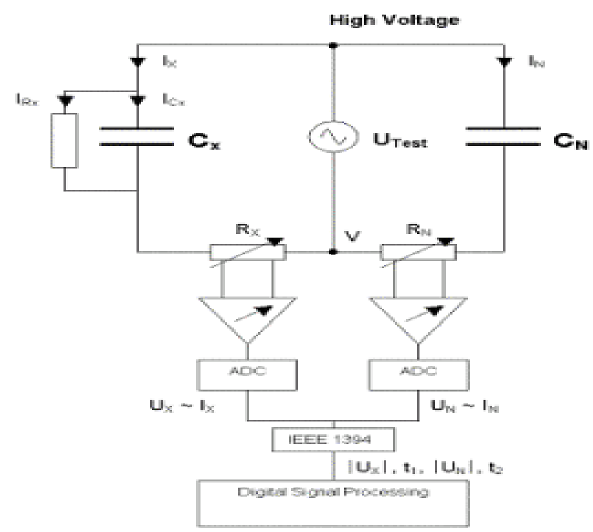

Fig. 2

I_X Current trough Device Under Test C_X
I_N Current trough known Standard Capacitor C_N
I_{RX} Losses of the Device Under Test C_X
C_X Test Object (ideal capacitance)
C_N Standard capacitor (with tan $\delta < 10^{-5}$)

R_X Measuring shunt for I_X, C_X
R_N Measuring shunt for I_N, C_N
V Low voltage point of the HV supply and reference point of the measurement

ADC Analogue to Digital Converter

t_1, t_2 Time stamps of the measured values

A case study of the 100kV/100pF Standard Capacitor showing its uncertainty measurements for capacitance and dissipation factor are shown in Table1 & Table 2. as per ISO/IEC 17025. [4]
Through this Bridge we can calibrate the Insulation of Transformers, Cables, Bushings, Circuit Breakers, insulators and Capacitors upto 200kV with current capacity upto 15Amps. Apart from this, the calibration of C & Tanδ bridges and Schering Bridges can also be done by comparison method.

The measurement uncertainties in the Capacitance & Tanδ measurements are 0.011% & 0.01% respectively.

Methodology of calibration

The accurate and precise calibration of High Voltage Capacitors & Tan δ measurements are accomplished by comparison method i.e. by comparing the capacitance of the capacitor under test to a standard reference capacitor as explained before. The comparison of capacitor value under test to that of a standard reference capacitor is done using high precision C, L and Tan δ measuring system as shown schematically in Fig 3. The capacitance value Cx (under test) can be measured online along with number of other pre-decided parameters e.g. voltage, currents (I_N, I_X), frequency, power factor etc. chosen from the library of the bridge, as required.[1]

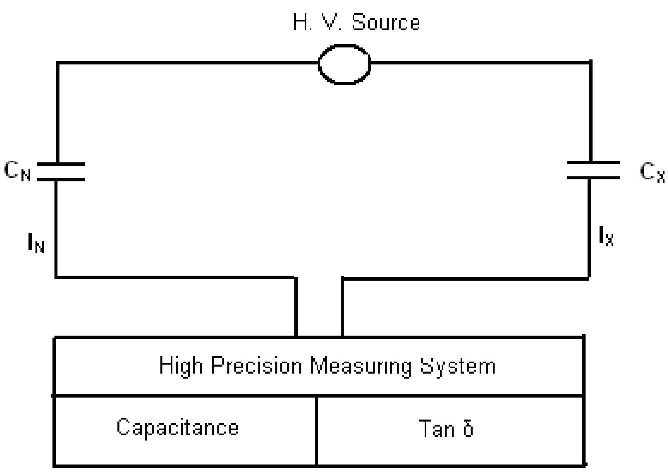

Fig. 3

Experimental Set up for the measurement of High Voltage Capacitor

Standards Used For Calibration

The standards used for the calibration of High Voltage Capacitors & Tan δ measurements are Standard Gas Capacitors: 200kV/100pF; 30kV/ 1000pF; Standard Air Capacitors: 2kV/100pF and 2kV/1000pF [3] and Standard High Precision C, L & Tan δ Measuring Bridge.

The uncertainty of this reference standard is 5 x 10^{-5} and is traceable to PTB Germany. The voltage applied on both the capacitors is varied from 0 to maximum as required and the corresponding Cx and Tan δ values are recorded online.[2],

Connecting Cables:

Proper cables with connectors are used for making connections to the reference capacitor and capacitor under test from the AC high voltage source. The output of the two capacitors are taken to the measuring bridge through standard flexible high quality fiber optical cables of up to 10 meters length with minimum losses.

Safety Precautions:

Test must be performed with the device under test completely de-energized and isolated from its power systems. The bridge must be solidly earthed with the same ground as the device under test. Testing of high voltage equipments involves energizing the equipment through a high voltage supply. This can produce dangerous level of voltage and current. Care must be taken to avoid contact with the equipment to being tested, its associated bushings, and conductors. Proper clearance between the test equipment and the device under test must be ensured during the presence of high voltage.

Results with Uncertainty Budget

After ensuring that the connections are proper and all safety precautions are observed then the calibration set up is switched on. Readings are recorded on line for capacitance after we get consistency. Type A uncertainty is calculated using the scatter and Type B uncertainties are taken for the instruments used and final value is calculated. Typical uncertainty calculation are given in table 1 and table 2.

1. Calibration Service: AC High Voltage Capacitor: Capacitance								
2. Methodology/Principle: Comparison Method								
3. Uncertainty of Standards Used: (i) STD. C & Tan δ Bridge							0.00010	
(ii) STD. Capacitor(200kV, 100pF)							0.00001	
CALCULATION OF MEASUREMENT UNCERTAINTY OF AC HIGH VOLTAGE CAPACITOR AT 100kV, 100pF								
Type A	Input no. of readings			**n =**	**6**			
		Readings (Xi)	**Measured Values (pF)**					
		X1	99.323					
		X2	99.323					
		X3	99.325					
		X4	99.324					
		X5	99.325					
		X6	99.324					
	Average		99.324					
	Standard Deviation		0.000894427					
	Standard Uncertainty		0.000365148					
	Degrees of freedom		5					
Uncertainty Budget								
Sources of error	limits		Probability distribution	Dividing Factor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
	(pF)				(pF)		(pF)	
Repeatability (U1)	0.0003651148		Normal (Type A)	1	0.000365148	1	0.000365148	5
U2 (STD. C & Tan δ Bridge)	0.00010		Normal, Type - B	2	0.00005	1	0.00005	infinity
U3 (STD. Capacitor 200kV, 100pF)	0.00001		Normal, Type - B	2	0.000005	1	0.000005	infinity
Combined Uncertainty in measurement:							**0.00036859**	**pF**
			Effective Degree Of Freedom:				**5.191168145**	
					Coverage Factor k = 2.52			
Expanded uncertainty (U)		k=2.52				**U = ±**	**0.000928846**	**pF**
The reported uncertainty is at coverage factor k=2.52, which corresponds to a coverage probability of approximately 95% for a normal distribution								

Table 1
Sample Calculation for the calibration of High Voltage Capacitance of 100kV/100pF capacitor at rated voltage 100kV

1. Calibration Service: AC High Voltage Capacitor: Tan δ	
2. Methodology/Principle: Comparison Method	
3. Uncertainty of Standards Used: (i) STD. C & Tan δ Bridge	0.00001
(ii) STD. Capacitor Tan δ (200kV, 100pF)	0.0001

CALCULATION OF MEASUREMENT UNCERTAINTY OF Tan δ OF AC HIGH VOLTAGE CAPACITOR AT 100kV, 100pF

Type A	Input no. of readings		**n = 6**
		Readings (Xi)	**Measured Values (Tan δ)**
		X1	**0.000001**
		X2	**0.000000**
		X3	**0.000001**
		X4	**0.000001**
		X5	**0.000000**
		X6	**0.000001**
	Average		0.000001
	Standard Deviation		5.16398E-07
	Standard Uncertainty		**2.10819E-07**
	Degrees of freedom		5

Uncertainty Budget

Sources of error	limits	Probability distribution	Dividing Factor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Repeatability (U1)	2.10819 E-07	Normal (Type A)	1	2.10819E-07	1	2.10819E-07	5
U2 (STD. C & Tan δ Bridge)	0.00001	Normal, Type -B	2	0.000005	1	0.000005	infinity
U3 (STD. Capacitor 200kV, 100pF)	0.0001	Normal, Type -B	2	0.00005	1	0.00005	infinity
Combined Uncertainty in measurement:						**0.0000502498**	

Effective Degree Of Freedom:		**16138868911**
	Coverage Factor k = 2	
Expanded uncertainty (U) k=2	**U = ±**	**0.0001005**

The reported uncertainty is at coverage factor k=2, which corresponds to a coverage probability of approximately 95% for a normal distribution

Table 2

Sample Calculation for the calibration of High Voltage Tan δ of 100kV/100pF capacitor at rated voltage 100kV

Conclusion

By measuring the capacitance and Tan-Delta of the insulation regularly on periodical basis, it is possible to ensure the operational unexpected breakdown. Dissipation factor (Tan-Delta) is one of the most powerful off-line nondestructive diagnostic tools to monitor the condition of solid insulation of various high voltage equipments.

Capacitance and Tan-Delta values obtained at the time of manufacturing the equipment insulation are treated as benchmark readings. Then by measuring and comparing the periodical readings of the capacitance and Tan-Delta of the insulating material with the benchmark readings, one can know the rate of deterioration of the health of the insulation. Knowing the rate of deterioration, we can predict the future unexpected breakdown of the insulation of the high voltage equipment, plan the maintenance schedule, repair the insulation before actual flashover, saving high cost of replacement of material,

Frequency of testing depends on history of past failures, environmental conditions, humidity, temperature & pollution etc.

Acknowledgement

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